Slowing down and straggling of protons and heavy ions in matter

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SUMMARY

The Doppler Shift Attenuation (DSA) method is widely used to measure lifetimes of nuclear states in the order of 10^{-14} to 10^{-11} s. In this method the nuclear state is populated after a nuclear reaction and decays by emission of a gamma ray, whilst the nucleus 'recoils' in its backing material. The energy shift of the gamma ray (which is measured) depends on the velocity of the recoil with respect to the detector at the moment of emission. So the lifetime of the nuclear state may be determined if the recoil slowing down process is known. However, many of the lifetimes resulting from DSA measurements display large variations which are caused by a lack of sufficient knowledge of these processes. That is why DSA measurements are also undertaken for nuclear states with well-known lifetimes. The measurement of 'ranges' is another often used method to study these slowing down processes. In this kind of measurement the distributions of implanted ions are determined for example by the method of Rutherford backscattering or from the yield curve of a resonant nuclear reaction. However, for both methods the slowing down of the particle beam used, which most often exists of α particles or protons, should be known.

In this thesis, research on energy-loss processes of protons and Si ions in aluminium is presented. The so-called Resonance Shift method has been improved for the measurements on the protons themselves. This method has only been used occasionally before. A new method has been developed, which is called the Transmission Doppler Shift Attenuation (TDSA) method, for the measurement on Si ions.

<u>CHAPTER 1</u> includes an introduction into the existing theories of energy loss of ions in matter. This introduction is intended for the reader who is not (or is no longer) familiar with atomic collision processes.

<u>CHAPTER 2</u> describes the experimental methods and the equipment used. In the Resonance Shift experiments, the resonance yield

curve measured at a clear part of the target, is compared with the resonance yield curve at another part of the same target, which is covered with a certain quantity of aluminium. Deconvolution of the last yield curve by the first one, results in the energy-loss distribution of the particle beam in the aluminium. In this project a proton beam of about 1 μA was used, and the 1375 keV resonance of the $^{34}S(p,\gamma)^{35}Cl$ reaction was studied. In this energy region the stopping is determined mainly by the interaction of the proton beam and the electrons in the aluminium. As a result the protons will be slowed down but not be deflected. The energy resolution of the Resonance Shift method proves to be about 100-200 eV which value is extremely good compared to the often used solid state detector which usually provides resolutions of 10-15 keV.

In the TDSA method the energy distribution of gamma rays emitted by a nuclear level, excited in a nuclear reaction, is measured. The energy distribution is a function of the velocity distribution of the emitting ions. In this case a study was made of the 1262 keV resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction. The resonant 12803 keV level decays partially to the 6878 keV level, which has a lifetime of 2.5 ps. The recoiling ^{28}Si nucleus has an initial kinetic energy of about 57 keV, which is equivalent to a velocity of 0.2% of the speed of light. The recoil will be slowed down by interactions with the electrons and nuclei of the target. The interaction with nuclei not only leads to energy loss but also to deflection of the recoils . So by measuring the Doppler shifted gamma-ray patterns information on the vectorial velocity distribution of the recoils at the very moment of decay can be obtained. In the past measurements of this type have been undertaken for recoils in thick targets with gamma-ray emitting nuclear states possessing well-known lifetimes of the same order as the recoil stopping time.

In the TDSA method thin targets are used so that a large fraction of the recoils has left the target before the gamma ray has been emitted. The mean life of the nuclear level studied should be long compared to the time it takes for the recoil to leave the target. This means that, effectively, the recoil-velocity distribution after leaving the target is being studied. In this way, it becomes possible to study the vectorial velocity distribution as a function of distance travelled by varying the thickness of the stopping layer.

The second chapter also gives a description of the characteristics of the Van de Graaff accelerator at Groningen and of the scattering chamber used.

CHAPTER 3 outlines the preparation of the very thin self-supporting aluminium targets for the TDSA measurements and of the Sb_2S_3 targets for the Resonance Shift measurements. All targets are prepared by the 'vacuum evaporation' method. Much effort was devoted to ensuring that the self-supporting aluminium targets were thinner than the range of the ^{28}Si recoils (± 300 atomic layers) and could withstand a 1262 keV proton beam of 1 μA for a period of several days. This chapter also reports on the structure, thickness uniformity and contamination of the targets.

CHAPTER 4 describes the computer programs which were used for the measurement analysis. A program called RESFIT was developed for the Resonance Shift measurement. This program is able to fit measured resonance yield curves for a given energy-loss distribution of the particle beam. An existing program called DOPSIM was adapted for the analysis of the TDSA measurements. DOPSIM simulates not only the scattering processes between the recoils and both the target nuclei and electrons, but also the emission of the gamma rays. The adaption makes it possible to use several different models for the screened Coulomb potential describing the nuclear scattering.

CHAPTER 5 discusses the results of the Resonance Shift measurements. In the energy region studied, and for stopping layers of up to 20 μg/cm^2, or 300 atomic layers, the energy-loss patterns of protons prove to be well described by the theory of Vavilov. An additional finding was that this distribution can be approximated by a trial function, which is a convolution of a normal distribution and an exponential function.

CHAPTER 6 describes the results of the TDSA measurements. For the analysis of the measurements the angular distributions of the gamma rays of the 12803-6878-0 keV cascade of the ^{28}Si nucleus must be known. These distributions were measured and their analysis confirms the $J^{\pi} = 3^{-}$ assignment of the resonant (12803 keV) level, as previously found by Nordhagen. The program RESFIT was used to calculate the proton-beam energy relative to the resonance energy. This program was also used to determine the thicknesses of the targets, and to calculate the distribution of the starting points of the recoils, over the targets. In these aspects the results of the Resonance Shift measurements are essential for the analysis of the TDSA measurements. From the latter measurements it is concluded that the theory of Lindhard, Scharff and Schiøtt describes the slowing down of the 57 keV Si recoils in aluminium very well. In the fitting of the theory to the experimental results, the often used scaling factors f_N and f_E for nuclear and electronic stopping, prove to be about unity, and thus redundant. The analysis showed no significant differences, in this energy region for either the Thomas-Fermi interatomic potential as used by Lindhard et al., or the interatomic potentials of Molière, or of Lenz-Jensen. As a supplement to other methods such as range measurements, Rutherford Backscattering measurements, and transmission measurements as described in chapter 1, the TDSA method has proven to be valuable to determine the characteristics of the interatomic potentials.